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INSTITUTE OF ENGINEERING RESEARCH
BERKELEY, CALIFORNIA

Forms of Equilibrium of Coasts with a Littoral Drift

By

Per Bruun

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62

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Technical Report
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Forms of Equilibrium of Coasts with a Littoral Drift

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Berkeley, California
February, 1953

Forms of Equilibrium of Coasts with a Littoral Drift**

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ABSTRACT

It is shown that the form of some coastal features where a littoral drift exists can be explained by the solution of a very simple differential equation for the relationship between the intensity of littoral drift and the deep water of the waves. Other beach forms under less idealized conditions may be explained from a similar relation. Different types of marine-forelands can be explained as a result of refraction and diffraction in connection with a lowering of the steepness ratio of the waves.

1. DEFINITION OF AN EQUILIBRIUM COASTLINE

A coastline has an equilibrium form when it maintains its geometrical form.

2. EQUILIBRIUM FORMS OF COASTLINES OF INFINITE LENGTH

2.1 The Coast is Influenced by Waves Perpendicular to the Coastline. Fig. 1 shows a straight sand or shingle-coast of infinite length. The direction of wave propagation is as indicated. Under the conditions given, no littoral drift can occur along the coast which is in stable equilibrium.

2.2 The Coast is Influenced by Waves Oblique to the Coastline. Fig. 2 shows a straight sand or shingle coast of infinite length. The direction of wave propagation is as indicated. The littoral drift at "b" must be equal to the littoral drift at "a" and the coast, therefore, is in stable equilibrium.

3. EQUILIBRIUM FORMS OF COASTLINES WITH A FINITE LENGTH

3.1 A Straight Coast of Limited Length. If in Fig. 2 the length of the coast is limited from "d" to "c" it will be eroded. The erosion will be greatest at "d" and will decrease towards "c". As a consequence of this condition the coastline will be reoriented to "face" against the waves.

3.2 An Island or a Headland

3.21 Theoretical considerations. Fig. 3 shows an island. If the direction of wave propagation is not perpendicular to the coastline "a-b" or if the corners at "a" and "b" are not absolutely sharp, erosion will begin.

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* Fulbright Fellow, Univ. of Calif., Berkeley, and Research Engineer, Tech. Univ. of Denmark, Copenhagen.

** The principles presented in this report first appeared in the publication "Ligevaegtsformer for Materialvandringskyster" by Per Bruun, Geografisk Tidsskrift, Vol. 48, 1946-47. Because a summary of this publication is not readily available to American engineers, this report has been prepared by Mr. Bruun.

According to the theory of Munch-Petersen the relationship between the littoral drift and the deep water angle α_0 can be illustrated by a sine curve (2, 8)*. This theory is supposed to be reliable. The terms "zero point of littoral drift" and "mass curve of littoral drift" are introduced. A "zero point" (called "nodal point" in the United States) is the point of a coastline, where the resulting littoral drift, considering plus or minus signs which correspond to the direction of the drift, is equal to zero. In Fig. 5 point O is a nodal point. The "mass-curve of littoral drift", Fig. 4, is the curve which will result when in a right-angled coordinate-system the length of the coast from the nodal point is taken as abscisse, and as ordinate the quantity of material (sand, gravel, etc.) which in a given period is eroded between the nodal point and the point in question. The nodal point has the coordinates O, O. From the coast with length s, B cubic meters of material are eroded. $\frac{dB}{ds}$ is equal to the erosion per meter of the coastline. When the mass-curve is a straight line, $\frac{dB}{ds}$ is constant, i.e. the eroded quantity per meter of the coast is the same at all points, which again means that the coastline maintains its form. Fig. 5 shows a coastline with $\frac{dB}{ds}$ = constant. This coast is composed of the same sort of material (sand and gravel) everywhere and is attacked by waves perpendicular to the coastline at the nodal point o. The eroded material can pass freely at any point. From the above it is noted that for the point x,y, which is the distance s from O on the coastline (Fig. 5):

$$k \cdot s = A \sin\alpha_0$$

where k is a constant. A can be identified as the wave-effect, and α_0 is the deep water angle of the waves. Solution of the differential equation gives the curve:

$$x = \frac{A}{k}\left(\frac{\sin 2\alpha_0}{4} + \frac{\alpha_0}{2}\right) \qquad 0 \leq \alpha_0 \leq \frac{\pi}{2}$$

$$y = \frac{A}{k}\left(\frac{\sin^2\alpha_0}{2}\right)$$

These are equations of a cycloid, with the diameter of the corresponding circle being $\frac{A}{2k}$. Naturally all equilibrium forms are uniform.

In Fig. 6, A inclines to the coastline. The form developing is that given by the above equations between the angles $(90-\alpha_0)^\circ$ and 90°.

3.22 <u>Typical Examples</u>. Several typical examples have been shown as follows (for their location in Denmark, see Fig. 7):

<u>Example 1</u>, Hundested, Sjaelland (Fig. 8) The actual nodal point can be stated by means of the groins constructed at Kikhavn.
<u>Example 2</u>: the peninsula Skoven, Fyn, (Fig. 9)
<u>Example 3</u>: Barsoe (oe = island) (Fig. 10)

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* Numbers refer to references.

Example 4: Bjornoe (Fig. 11)
Example 5: Endelave (Fig. 12)
Example 6: Fejoe (Fig. 13)
Example 7: Skagen Spit, the northernmost part of Jylland (Jutland) (Fig. 14). Figure 15 shows an aerial photograph of Skagen Spit from 10,000 ft. The area of the photo is shown with dotted lines in Fig. 14. Note the sand-cloud of material being transported in suspension.

3.23 Development of an equilibrium coastline in the laboratory. Fig. 16 shows an equilibrium form developed in a laboratory basin in Copenhagen. Naturally it is impossible to imitate actual conditions and the result can only be taken for granted for this special case. The basin was 35 ft. long, 15 ft. wide, with a water depth of 5 inches. The wave characteristics were Lo = 4 ft.-4 in., Ho = 2in., i.e. $\frac{Ho}{Lo} = 0.04$. The median diameter of the sand, was 0.22 mm., and the uniformity coefficient (D60%/D10%, in Denmark) was about 2. The scale was 1:20 corresponding to the shingle beaches along the Danish seas.

Several equilibrium forms were developed. Some of them showed a tendency to form a bump at $\alpha_0 \sim 40\text{-}50^\circ$. The same condition has been observed in recurved spits (see also Sections 3.32 and 3.33).

3.3 A Bay

3.31 Theoretical considerations. The condition shown in Fig. 17a and b assumed that the island-form can be reversed to give a similar bay-form by changing land and sea.

3.32 Typical examples. It is very difficult to find areas in nature where a bay-shoreline like this can be investigated. The initial condition must be an indentation with vertical sides and infinite length in one direction. Fig. 18 shows the bay of Vemmingbund in Denmark (Example 8 in Fig. 7). From the figure it will be seen that the coastline deviates from the theoretical form between 40° and 70° - the actual form having sharper corners. Fig. 19 shows Abbotts lagoon on the Pacific Coast of the United States. Here we have the same deviation from the theoretical form as in Fig. 18.

3.33 Some special investigations. In order to investigate the problem more distinctly, studies were conducted in two small oblong sand-bays in the Nissum Inlet on the West Coast of Jylland (see Fig. 7, "Nissum F,"). The bays had a reasonable size in proportion to the wave length - width 10-30 times the storm-wave length. The form of the shoreline was measured every month during a period of about 2 years. Fig. 20 shows a characteristic measurement where the black points indicate the shoreline. A groin was built in the nodal point to isolate the test-area. Included in the figure is a theoretical equilibrium form, and one can see that the theoretical form again has a shorter radius of curvature than the actual between 40° and 70° angle of incidence. The curvature is smallest between 40° and 50° which indicates that the littoral drift probably has its maximum rate between 40° and 50°.

Other investigations by which the shoreline was maintained in the theoretical position by means of gravel showed that deposits started

at about 20-25° angle of incidence, i.e., the littoral drift at 90° and at 20-25° was almost the same. By measuring the length of the shoreline from the nodal point at the groin (Point VII in Fig. 20) and the deep water angle, α_o, it is now possible to establish the relationship between the quantity of littoral drift and α_o as shown in Fig. 21.

According to the size of the bay considered in relation to the waves there can be only a slight difference between the conditions along a straight coastline and at the bay-coast. The curve will follow the equation $y = 0.57\ (\sin\alpha_o + \sin 2\alpha_o)$. Naturally this relationship can only be of an approximate character. The quantity of littoral drift depends on many different factors involving the steepness ratio of the waves, the beach profile, the beach material, etc. Laboratory experiments have shown that a variation in the steepness ratio did not change the value of α_o for which the littoral drift was a maximum (7).

As stated in Section 3.23 at many recurved spits there is a tendency for bumps in the coast to form at 40-50°. In most cases the shorelines will follow the theoretical form, and one must assume that this is due to a concentration of streamlines, cf. Fig. 22, which makes the sine-relationship valid.

3.34 <u>Comparison between different computed equilibrium forms.</u> Below are given three different equations for the relationship between the quantity of littoral drift and α_o. The corresponding equilibrium forms are shown in Fig. 23.

1. $s = \sin 2\alpha_o$, maximum at 45°

   Equilibrium form: $x = 2\left(\sin\alpha_o - \frac{2\sin^3\alpha_o}{3}\right)$

   $y = 2\left(\cos\alpha_o - \frac{2\cos^3\alpha_o}{3} - \frac{1}{3}\right)$

2. $s = \frac{\sin\alpha_o + \sin 2\alpha_o}{2}$, maximum at 54°

   Equilibrium form: $x = \frac{\alpha_o}{4} + \frac{\sin 2\alpha_o}{8} + \sin\alpha_o\ \frac{2\sin^3\alpha_o}{3}$

   $y = \frac{\sin 2\alpha_o}{4} + \cos\alpha_o - \frac{2\cos^3\alpha_o}{3} - \frac{1}{3}$

3. $s = \frac{3\sin\alpha_o + \sin 2\alpha_o}{4}$, maximum at 68°

Equilibrium form: $x = \frac{1}{4}\left(\frac{3}{2}\alpha_o + \frac{3}{4}\sin 2\alpha_o - \frac{4}{5}\sin^3\alpha_o + 2\sin\alpha_o\right)$

$y = \frac{1}{4}\left(-\frac{3}{4}\cos 2\alpha_o + 2\cos\alpha_o - \frac{4}{3}\cos^3\alpha_o + \frac{1}{12}\right)$

The equilibrium forms are shown in Fig. 23 together with the form $s = \sin\alpha_o$ (indicated as Curve 0). It will be noted that a current parallel to the y-axis in a positive direction will draw the curves 1, 2 and 3 towards the Curve 0, but this possibly can make the resulting equilibrium form more rounded than the equilibrium form 0. Naturally this can only explain the development very roughly.

Fig. 24 shows the curves: $y = \sin\alpha_o$ (full line); $y = \sin 2\alpha_o$ (dotted line); and $y = 0.57\ (\sin\alpha_o + \sin 2\alpha_o)$ (dot and dash line); and some balck points originating from the Los Angeles District Engineer Office formula for littoral drift (6, pp. 145-149), i.e.:

$$Q = \frac{1}{2}\, k_1\, w\, e\, \sin 2\alpha_b$$

Q = littoral drift factor, the total amount of sand moved as littoral drift past a given point per year by waves of given periods and direction.

w = total work accomplished by all waves of a given period and direction in deep water during an average year.

e = wave energy coefficient at the breaker line for waves of a given period and direction. It is the ratio between the distance between orthogonals in deep water and at the shore line.

α_b = angle between wave crests at the breaker line and the shore line, or the angle between orthogonals and the normal to the shore line.

k_1 = factor depending on dimensional unity and empirical relations. It varies with beach slope, grain size, and other undertermined variables and has not been evaluated.

One has: $e = \dfrac{\cos\alpha_o}{\cos\alpha_b}$

or

$$e \sin 2\alpha_b = 2 \cos\alpha_o \sin\alpha_b$$

In Fig. 25 is shown plots for the relationship between $\sin\alpha_b$ and $\sin\alpha_o$ for $\frac{Ho}{Lo} = 0.04$, 0.03, and 0.01, see (4), pp. 398-400. Each of the curves can be approximated with a straight line between 0° and about 50°. For instance, one has for $\frac{Ho}{Lo} = 0.04$, $\sin\alpha_b = \frac{1}{2}\sin\alpha_o$; that is: $2\cos\alpha_o \sin\alpha_b = \frac{1}{2}\sin 2\alpha_o$, which gives a maximum at 45°. Calculations with a steepness ratio, $\frac{Ho}{Lo} = 0.04$, give the black points in Fig. 24, but the other ratios will give almost the same relationship. Thus it appears as though the maximum value of the littoral drift will occur between 40° and 50°. Saville (3, 9) got the same result in his experiments. The Bulletin of the Beach Erosion Board (3) states that "The experiments indicate, for the range of angles tested, that the transport rate is dependent upon the littoral current. Further, the maximum rate of sand transport occurred where the value of the littoral current reached a maximum value, namely at a 43° deep water angle."

4. THE DEVELOPMENT OF SOME SPITS

J. A. Steers writes (Ref. 11, p. 60) as follows:

"Associated with the whole question of wave action and beach-drifting is another interesting matter first pointed out clearly by Lewis. If an inspection be made of the main spits of shingle around our coasts on large-scale maps it is clear that many of them have a tendency to run somewhat outwards and away from the main trend of the coast. This is especially plain in Cardigan Bay: both Morfa Dyffryn and Morfa Harlech, the two main coastal forelands, are good illustrations. On the east coast, Blakeney Point and Scott Head Island also exemplify the same feature. Again, on the south coast, Dungeness and the smaller Hurst Castle spit trend outwards from the coast, and it would be easy to cite a number of other instances. Many beaches between headlands are arranged, too, so as to show a clear tendency to run at right angles to the main direction of wave approach, a characteristic discussed more fully below."

The development of Dungeness is very complex (see Ref. 11, pp. 318-331), but roughly it may be explained as follows:

If α_0 is greater than about 50° the quantity of littoral drift must be below maximum. Meanwhile the littoral drift is satiated very fast at shingle-beaches, and the material will deposit if a slight decrease in the littoral drift forces takes place. As a consequence of this, the shoreline must turn outward if more material is drifting along the coast. At last the value of α_0 which gives the maximum littoral drift will be passed and deposition must take place, giving rise to a sudden turn-out of the shoreline until it is perpendicular to the direction of wave propagation as shown in Fig. 26. In this figure the letters (alphabetic order) show the development of Dungeness (also see Ref. 12 for some pictures of this area).

A development similar to that mentioned above may take place at any shingle-beach where the direction of wave propagation is oblique to the shoreline.

5. OTHER COAST-FORMS

The development of some "marine forelands" can be explained as a result of wave refraction and wave diffraction, with the subsequent lowering of the steepness ratio of the waves. Figures 27, 28 and 29 show three different types of marine forelands from the Danish coasts (all are islands). They are described by Axel Schou in the book "The Marine Foreland", Copenhagen 1945 (10). Fig. 27 shows recurved spits, Fig. 28 tombolos and Fig. 29 an "angle-foreland".

Figs. 30, 31 and 32 show forelands developed in the Hydraulic Laboratory in Copenhagen which correspond to the prototype conditions shown in Figs. 27, 28 and 29. The laboratory basin was 35 ft. long, 15 ft. wide, the water depth was 5 in. The wave characteristics were L_0 = 4 ft. 4 in., Ho = 2 in. i.e., $\frac{Ho}{Lo} = 0.04$. The median diameter of the sand was 0.22 mm. and the uniformity coefficient, D60%/D10% was about 2. The scale was 1:20 which corresponded to shingle-beaches along the Danish seas. The form illustrated in Figs. 27 and 30 result from refraction. The forms in Figs. 28 and 31 and Figs. 29 and 32 result from diffraction and refraction giving a lowering of the steepness ratio of the waves.

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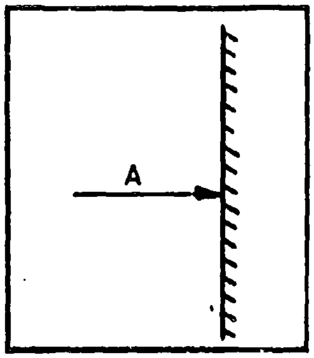
12. Steers, J. A. (1948), A Picture Book of the Whole Coast of England and Wales, Cambridge University Press.


A

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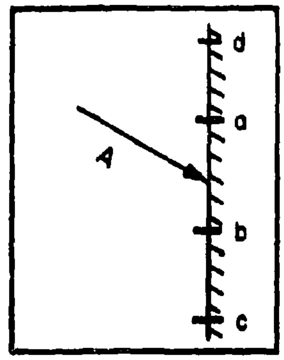
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b
c

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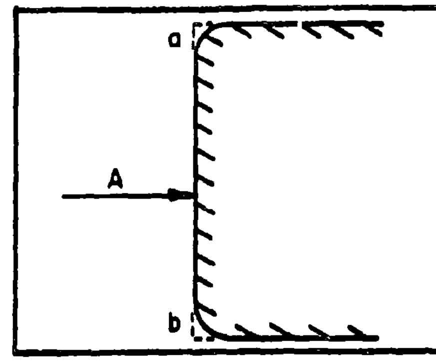
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b

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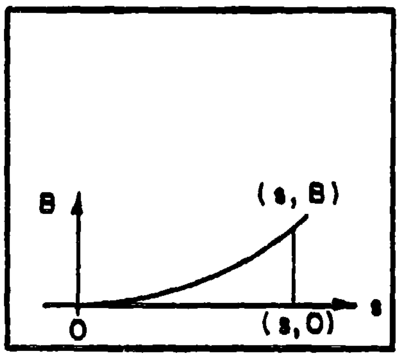
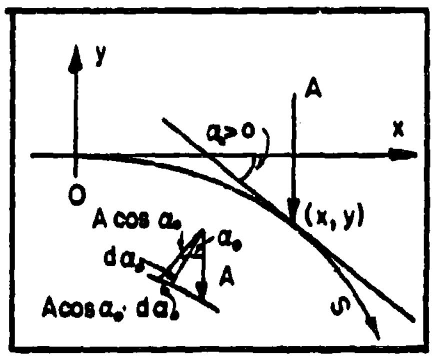
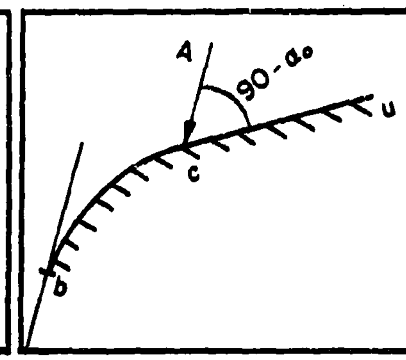

B
(s, B)
O
(s, O)
s

4.


y
A
x
$a_0 > o$
O
$A \cos a_0$
a_0
(x, y)
da_s
A
$A \cos a_0 \cdot da_s$
S

5.


A
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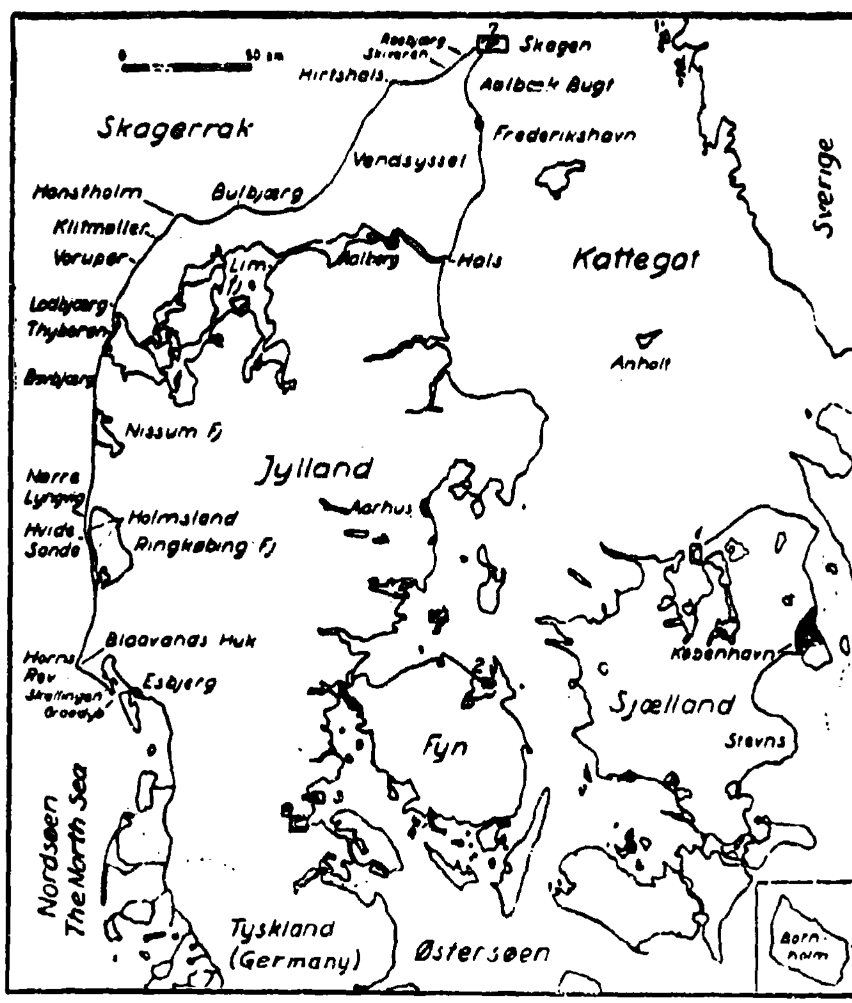
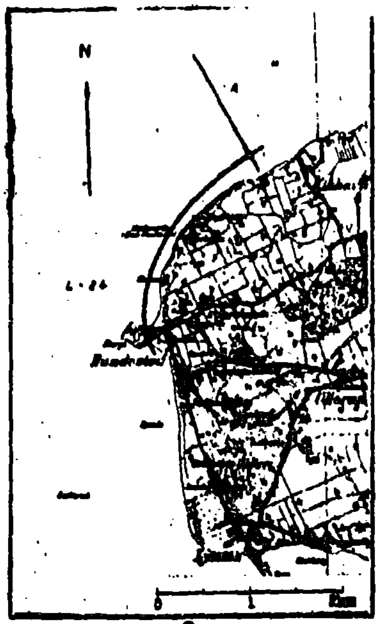
u
c
b

6.


Skagen
Hirtshals
Aalbæk Bugt
Frederikshavn
Skagerrak
Vendsyssel
Hanstholm
Bulbjerg
Klitmøller
Vorupør
Lim fj.
Aalborg
Hals
Kattegat
Sverige
Lodbjerg
Thyborøn
Anholt
Nissum Fj
Jylland
Nørre Lyngvig
Holmsland
Hvide Sande
Ringkøbing Fj
Aarhus
Blaavands Huk
Horns Rev
Esbjerg
København
Sjælland
Fyn
Stevns
Nordsøen
The North Sea
Tyskland
(Germany)
Østersøen

7.



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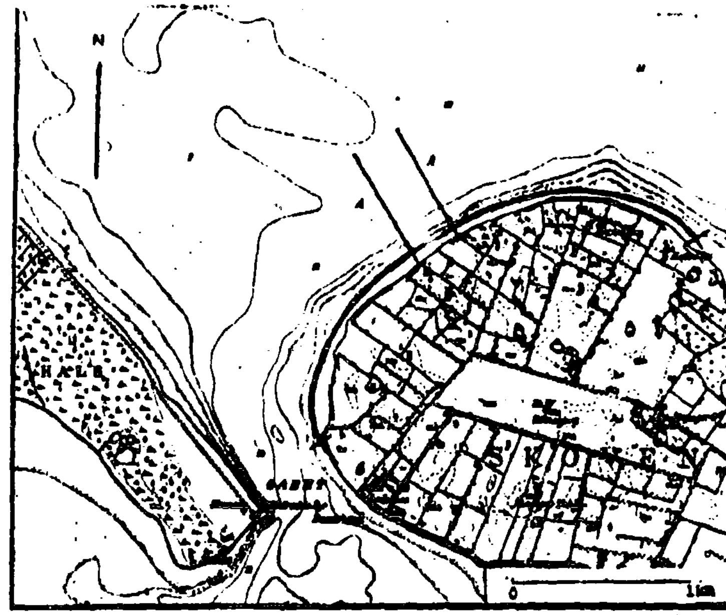

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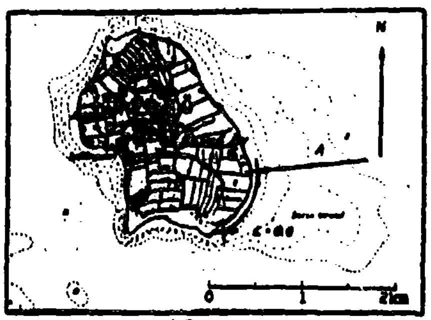

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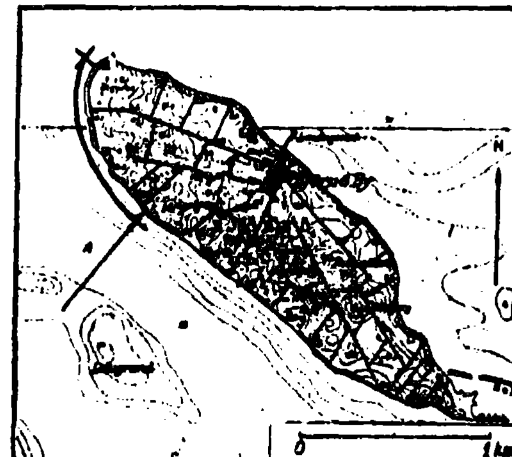

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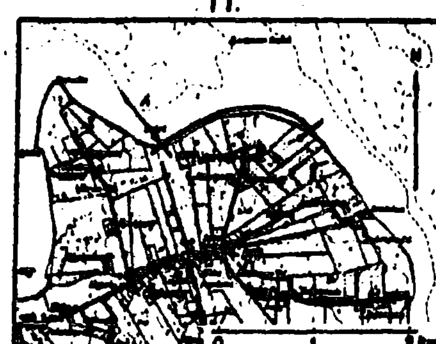

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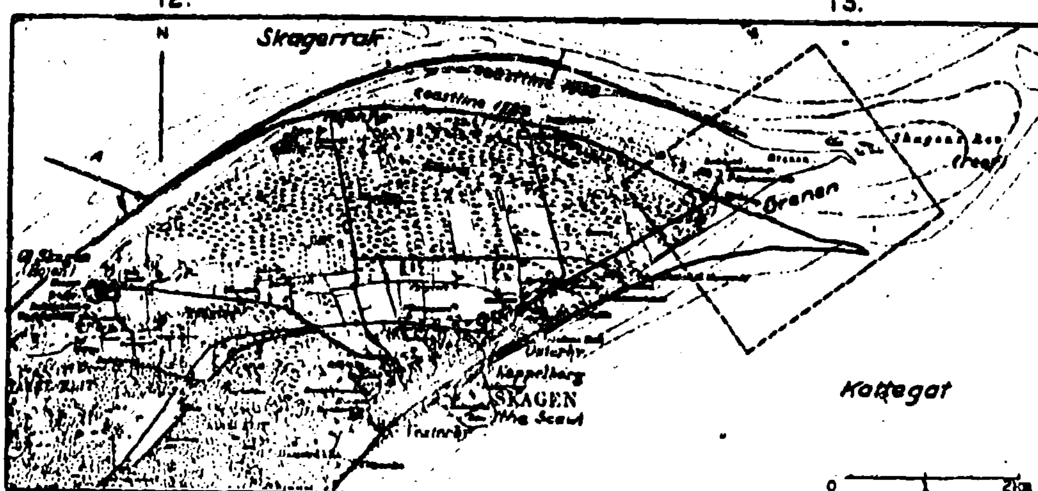

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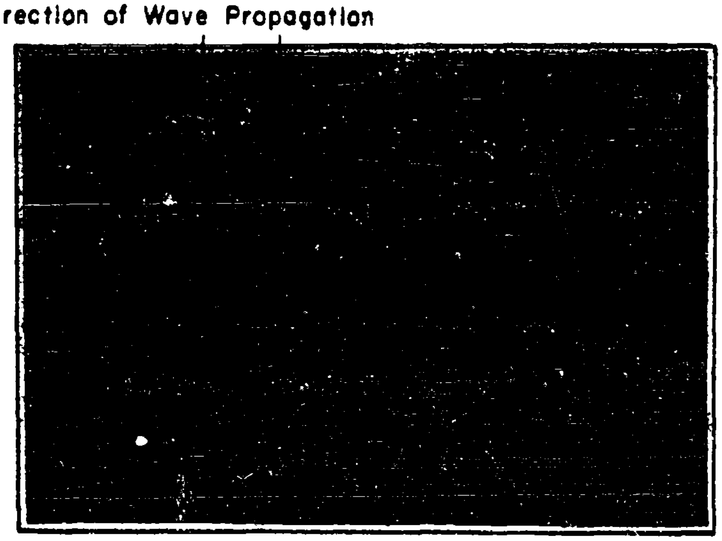

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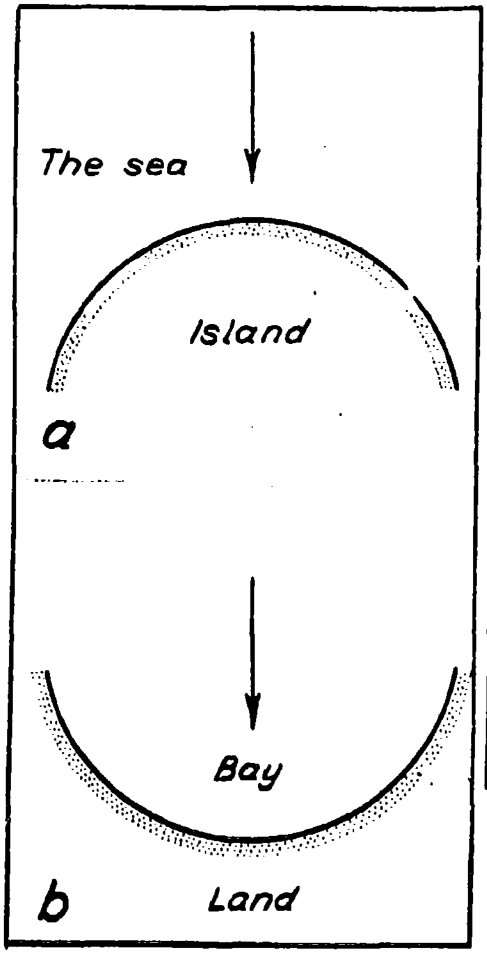
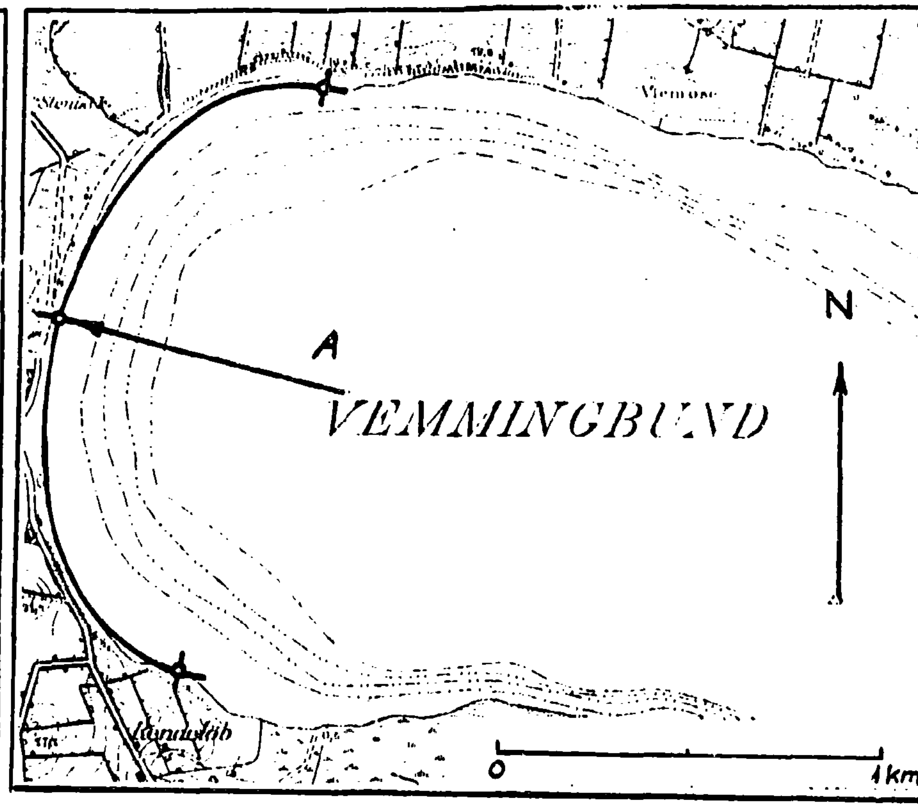

The sea
Island
a
Bay
b
Land

17.


A
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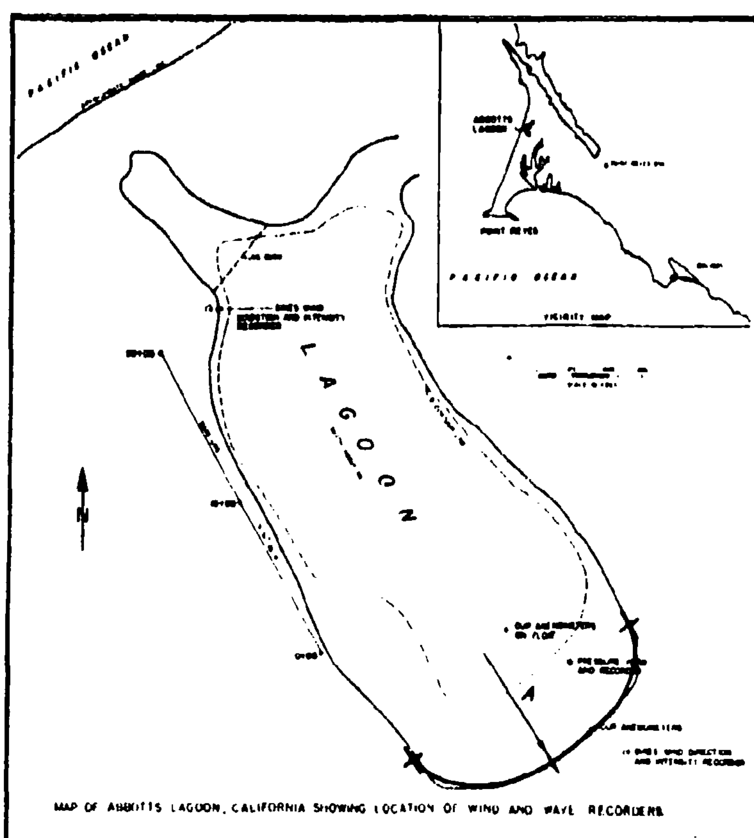
PACIFIC OCEAN
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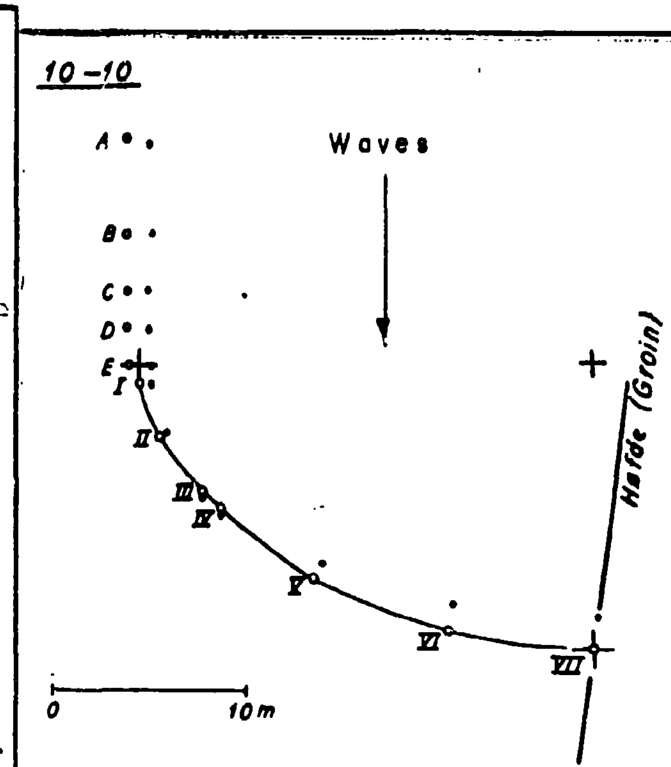
POINT REYES
MAP OF ABBOTTS LAGOON, CALIFORNIA SHOWING LOCATION OF WIND AND WAVE RECORDERS

19


10 –10
Waves
A
B
C
D
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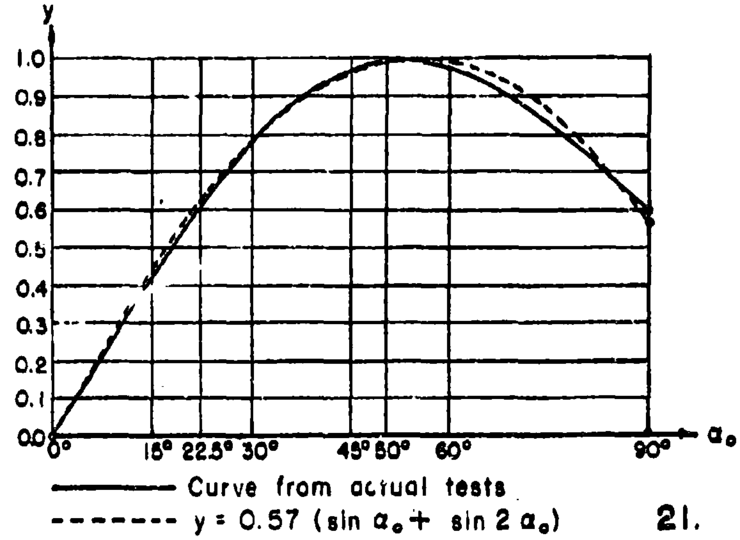
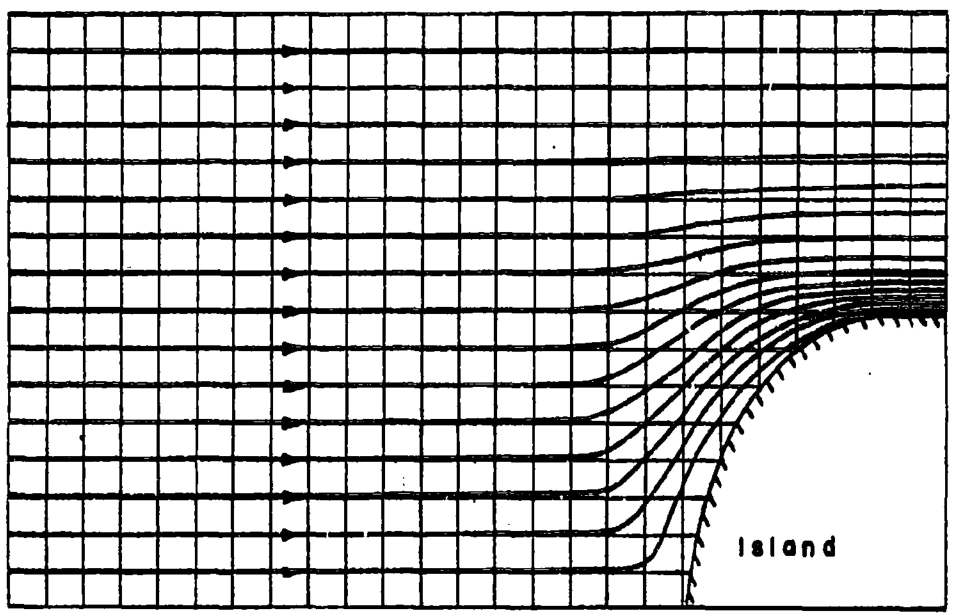
II
III
IV
V
VI
VII
Høfde (Groin)
0
10m

20.



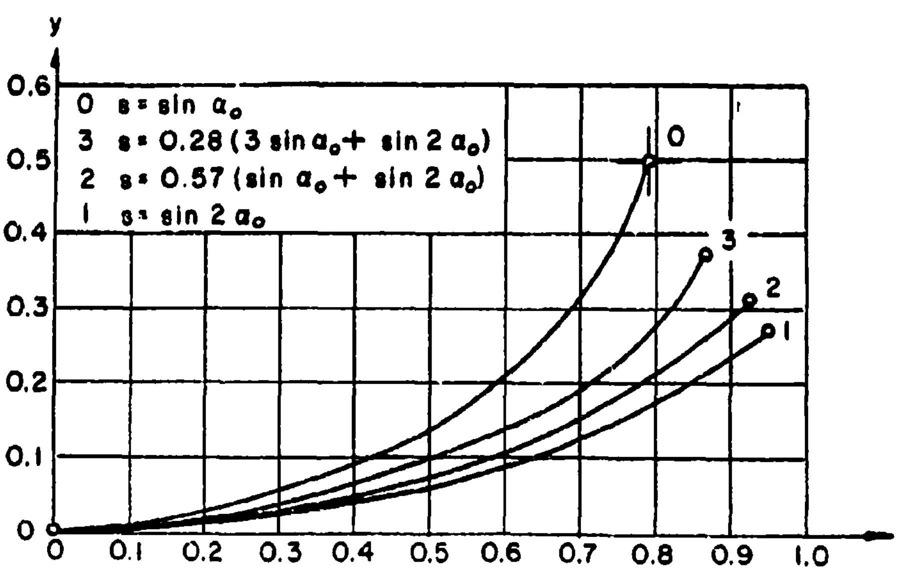
y
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0°
15° 22.5° 30°
45° 50° 60°
90°
α_o
Curve from actual tests
$y = 0.57 (\sin \alpha_o + \sin 2\alpha_o)$

21.



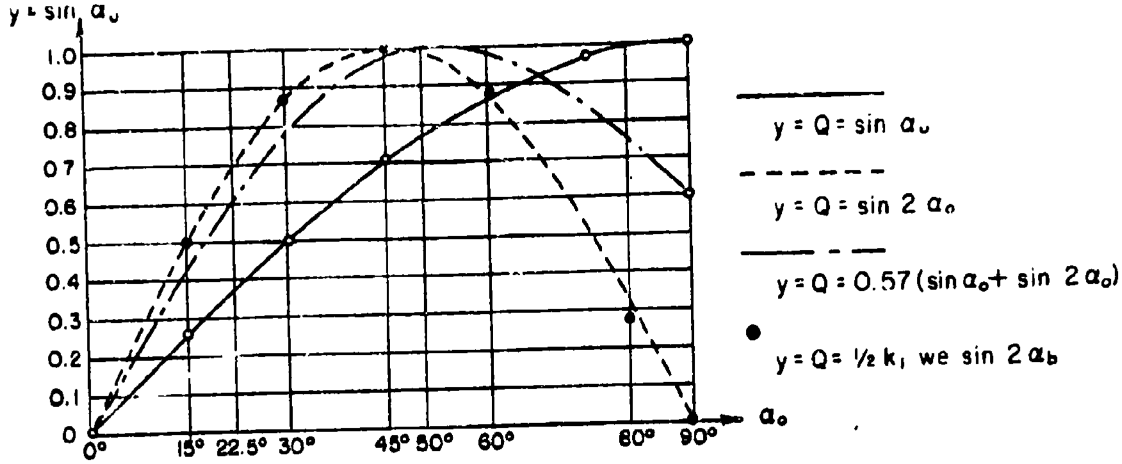
Island

22.

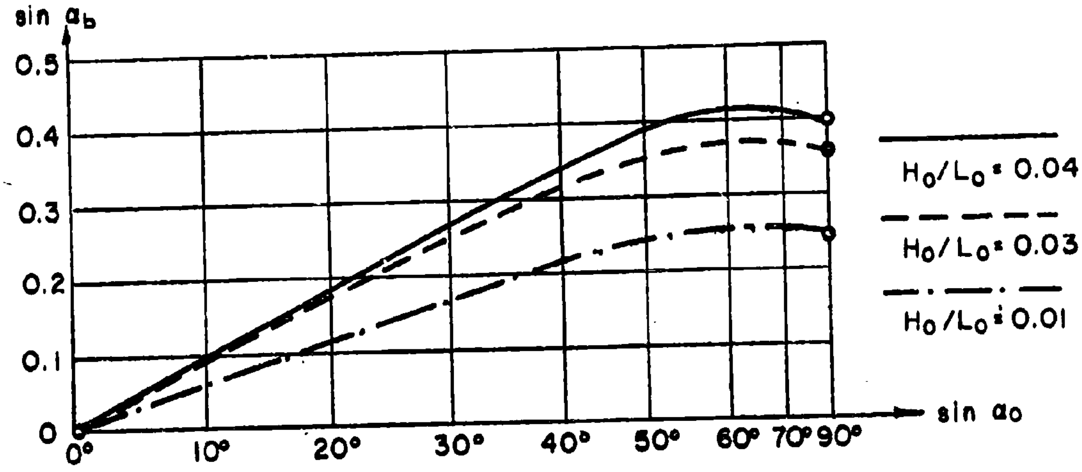


y
0.6
0.5
0.4
0.3
0.2
0.1
0
0 s = sin α_o
3 s = 0.28 (3 sin α_o + sin 2 α_o)
2 s = 0.57 (sin α_o + sin 2 α_o)
1 s = sin 2 α_o
0
3
2
1
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
x

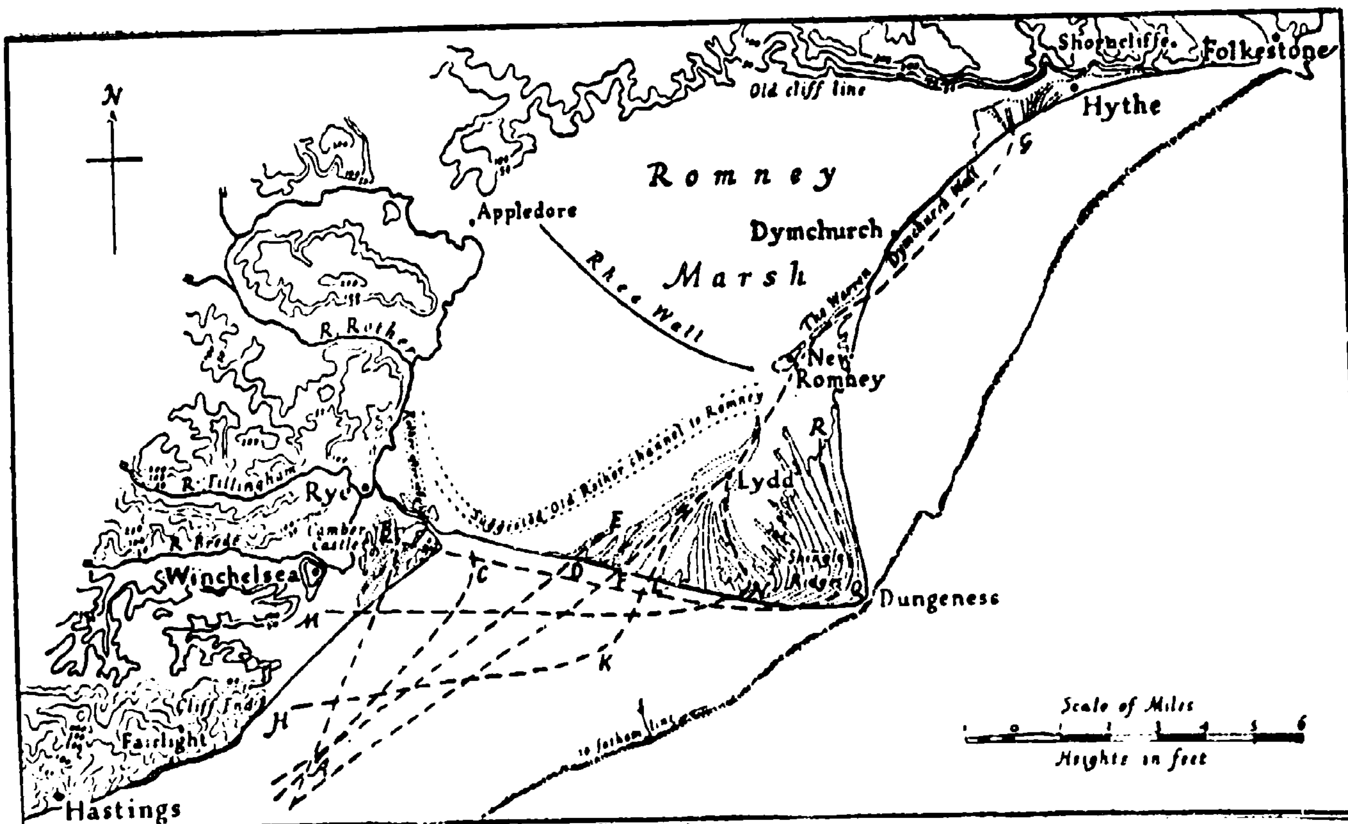
23.


y = sin α₀
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0°
15°
22.5°
30°
45°
50°
60°
80°
90°
α₀
y = Q = sin α₀
y = Q = sin 2 α₀
y = Q = 0.57 (sin α₀ + sin 2 α₀)
y = Q = ½ k₁ we sin 2 α_b

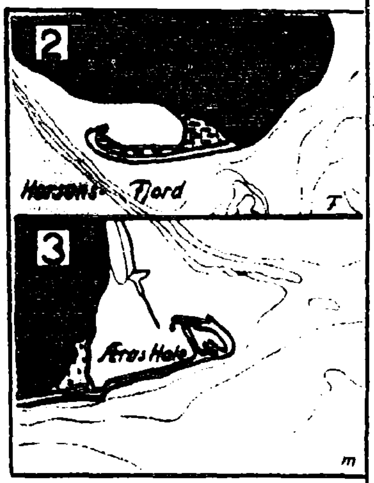
24.


sin α_b
0.5
0.4
0.3
0.2
0.1
0
0°
10°
20°
30°
40°
50°
60°
70°
90°
sin α₀
H₀/L₀ = 0.04
H₀/L₀ = 0.03
H₀/L₀ = 0.01

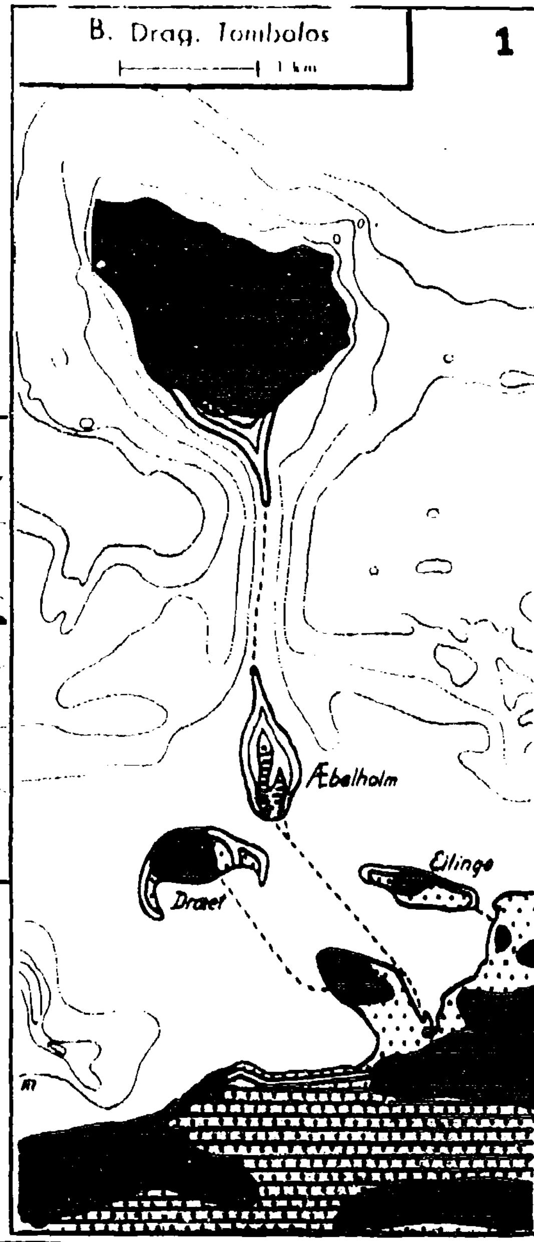
25.


N
Shorncliffe
Folkestone
Old cliff line
Hythe
Romney
Appledore
Dymchurch
Dymchurch Wall
Marsh
Rhee Wall
The Warren
New Romney
R. Rother
R. Tillingham
Rye
Old Rother Channel to Romney
Lydd
R. Brede
Camber Castle
Winchelsea
Shingle Ridges
Dungeness
Cliff End
Fairlight
Hastings
10 fathom line
Scale of Miles
Heights in feet

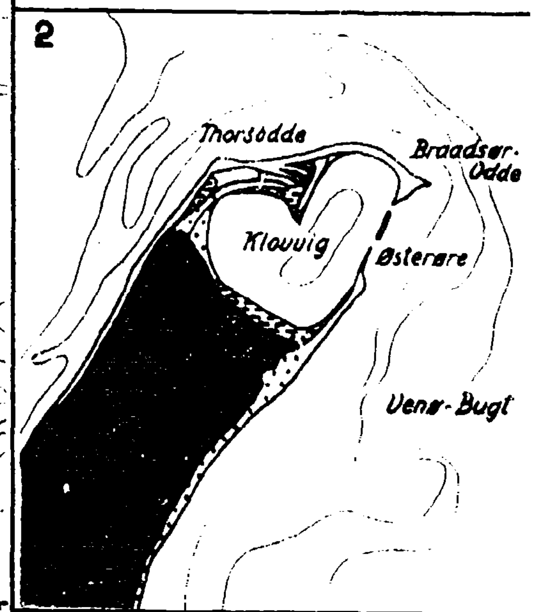
26.



27.



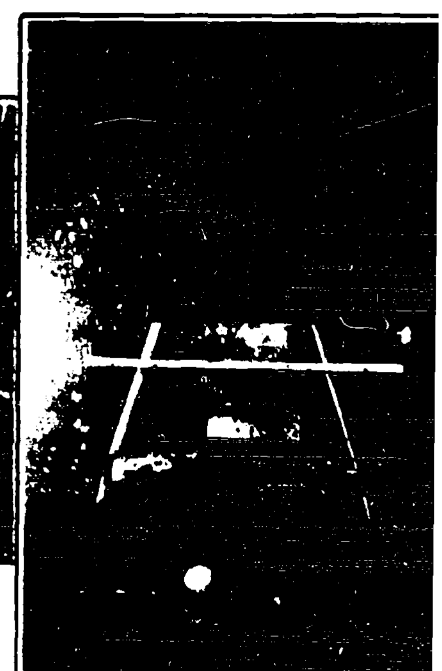
28.



29.

30.

31.



32.

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